EFFECT OF THERMAL CYCLING ON FATIGUE BEHAVIOUR OF WELDED STEEL

by

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CERTIFICATE

This is to certify that this work on " Effect of thermal cycling on fatigue behaviour of welded steel" has been carried out by Mr. B.B. Verma under my supervision, and it has not been submitted elsewhere for a degree.

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I.I.T. Kanpur. B.B. Verma

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ABSTRACT

Metal arc fusion welded mild steel joints have been subjected to thermal cycling treatment in the temperature range of $650^\circ - 910^\circ C$ with a view to refine as welded structure and study the effect of refined structure on the fatigue behaviour of the joints. The fatigue tests have been performed on unnotched and notched specimens, over a stress range, 0 to +ve stress values less than ultimate strength of the base material. It has been observed that thermal cycling refines the microstructure considerably. However, fatigue behaviour is adversely affected. The crack propagation rate in the fusion zone has been found to be lower than that in the heat affected zone. The results have been explained in terms of oxide inclusions that are precipitated during thermal cycling treatment and threshold stress differences between the treated and untreated samples.

CHAPTER I

INTRODUCTION

1.1 Fusion welding process is extensively used for fabrication of steel structures. Strength of such structures very much depend upon the strength of individual welded joints. Ideally, the strength of the joints should be equal to or higher than that of the base steel used in the structure. But invariably it is not so because of the fact that the fusion welding involves localized heating of the base steel to high enough temperature to cause melting and then fusion. The localized high temperature heating brings in its wake number of structural changes in the base metal. The mechanical properties most affected are ductility, fatigue strength and fracture toughness, Static properties, viz, yield and ultimate strength are affected to much lesser extent.

1.2 Factors affecting fatigue behaviour of fusion Welded joints:

Following factors have been observed to affect the fatigue strength of the fusion welded joint:

1. Presence of Residual tensile stress
2. Weld defects
3. Rough surface and weld toe
4. Microstructural changes associated with the process of welding

1.2.1 Residual Stresses:

During the fusion welding process large scale thermal gradients are set up due to localized nature of heating and cooling. Metal in the fusion zone contracts on solidification during cooling, setting up tensile residual stresses in the transverse and longitudinal directions. These stresses and the applied external stress result in an early onset of the fatigue cracks at the surface and thus reducing the fatigue strength.

Fig.- 1.1 depicts the residual stress pattern set up during fusion welding (butt joint).

1.2.2 Weld Defects:

(i) Fusion welding involves formation of molten metal pool which subsequently solidifies. All those defects associated with solidification processing (altenatively casting) such as voids, inclusions and hot tears (cracks) may be found in the weld region in the absence of proper process control.

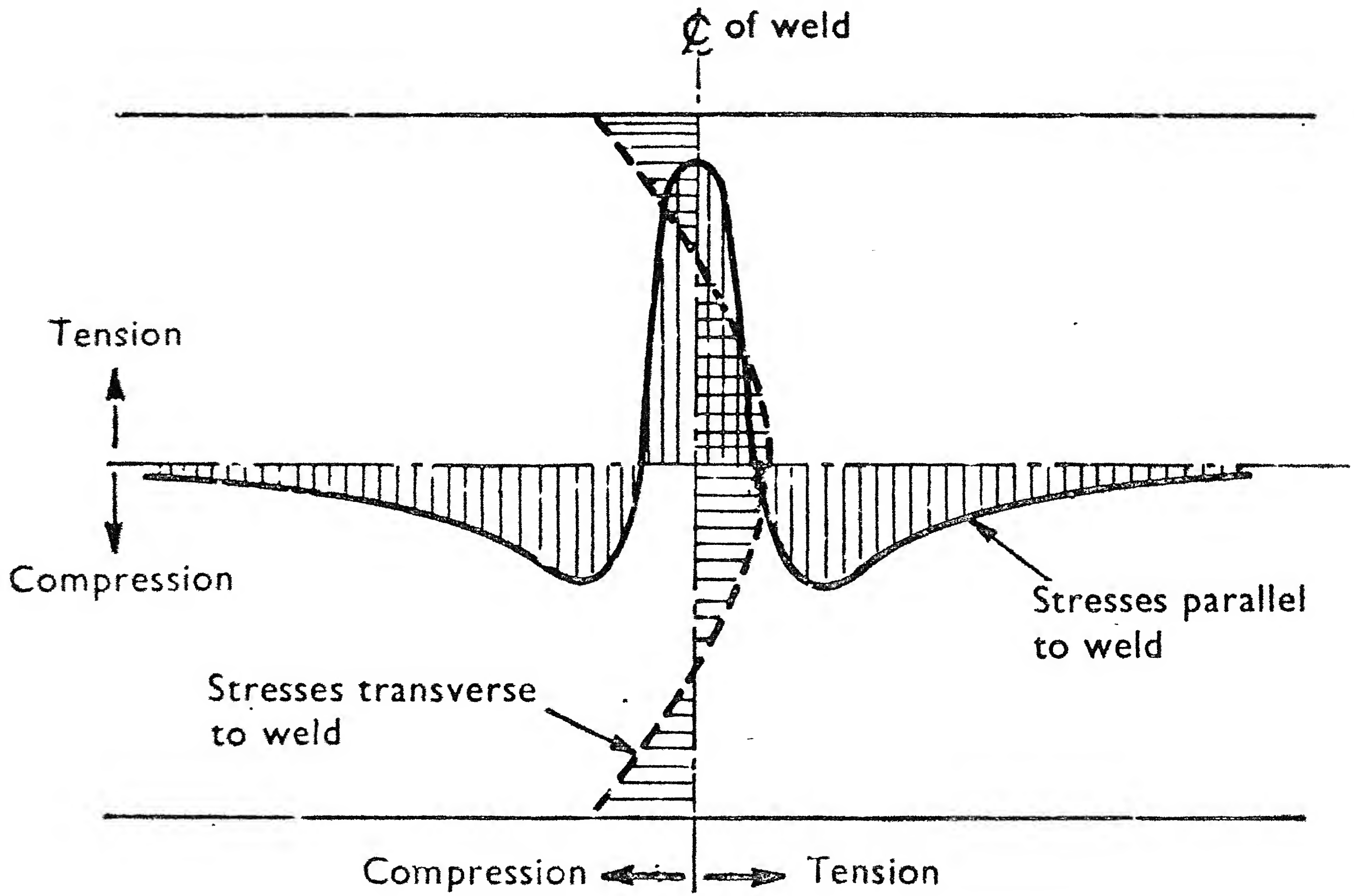


Fig. 1·1 Typical residual stresses around a butt-welded joint.

Besides the casting defects there are other ones viz. lack of fusion (of the base steel) and penetration (of the molten metal). Defects like voids, inclusions, crack and lack of fusion act as stress raisers and lower the fatigue strength considerably.

1.2.3 Effect of Rough surface and Weld toe:

The process of welding always forms a mill scale on the surface of the structure, making it rough and hence reduces the fatigue strength.

In the absence of weld defects, the major stress concentration in a specimen containing a transverse butt welded joint with the weld reinforcement left in the as welded condition occurs at the weld toe[1] (see Fig. -1.2) In such a specimen it is therefore from the weld toe, either of the top or of the back run, that fatigue failure invariably occurs.

1.2.4 Microstructural changes during fusion welding and its effect on fatigue behaviour:

The inherent characteristics of the casting process are present in the formation of a fusion weld. Nucleation and growth tendencies are influenced by the chilling action of the parent metal to produce a variable grain size within the weld. In multi-pass welding process each

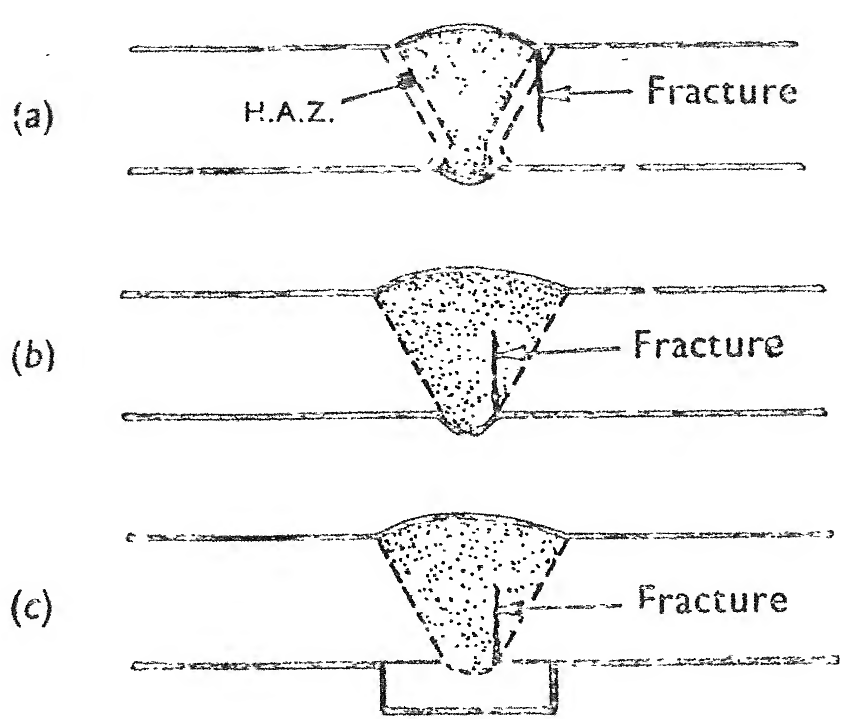


Fig. 1.2 Typical modes of fracture in specimens containing transverse butt welds: (*a*) in heat-affected zone material and parent plate initiated at weld toe; (*b*) (*c*) in weld metal initiated at the edge of the weld root.

succeeding pass forms a heat affected zone in the weld metal immediately below, and refines the grain in that region.

Generally five distinct zones form due to the process of welding, those are [2]: deposited metal having structure of cast metal, coarsened grain region, refined grain region, transition and unaffected region. The first phase that form during cooling of the molten metal in fusion zone is pro-eutectoid ferrite as a net-work or in parallel laths and high carbon transformation products such as fine pearlite and bainite form between the ferrite grains.

Coarsening of the grain takes place in the region where peak temperature exceeds the grain coarsening temperature .

Grain refinement occurs in the region next to the coarsened zone. The refinement of the grains indicates heating of the region just above A_3.

In the transition zone, a temperature range exists between A_1 and A_3 transformation temperatures where partial allotropic recrystallization takes place. Next to this zone is unaffected zone having the typical grain structure of the parent low- carbon steel which has not been heated to a high enough temp. to reach the critical range; hence, its structure is unchanged.

It is clear from above discussion that, process of fusion welding results a characteristic microstructural changes in the weld zone, and it is very much heterogeneous throughout the region. Normally, fatigue failure takes place in the weld zone of a welded structure and due to peculiar structural distribution, one can expect a quite different mode of crack initiation and propagation. The grain size distribution and its morphology may be one of the cause of lower fatigue strength of welded steel structures.

In addition to the changes in microstructure, welding also results in introduction of hydrogen into the material.

1.3 Methods of improving the fatigue life of welded joint:

It has been discussed in previous section that, in comparision to their static strength, the fatigue strength of welded joints is quite low. For better performance of the structure, it is therefore often desirable to use means of improving fatigue performance, and a number of possible methods will be discussed in this section .

1.3.1 Removal of residual stresses :

The process of fusion welding inherently suffers from the problem of residual tensile stress. So, simplest method for improving fatigue performance of welded joint is, relieving the residual tensile stress. Which can be done simply by subcritical annealing or by mechanical vibration in all directions. However, life can be improved further[3] by introducing a residual compressive stress at the notches at which fatigue cracks are likely to initiate. The techniquesare : Prior over loading, Peening, Local compression, Spot heating and Gunnert method.

1.3.2 Production of defect free welds and machining of toe:-

Defect free welding is very importent requirement for nice fatigue service of the structure. Though advance processes of welding like GTA welding, SAW, ESW etc.yield relatively defect free joints, control of defects is a tough job if welding is done by most popular manual arc welding process. High basic, deep penetrating electrode, high welding current and proper welding conditions are helpful in control of defects.

The stress concentration resulting from the formation of 'toe' leads to lowering of fatigue strength. Toe can be eliminated by grinding or machining the excess portion of the weld deposit and smoothening the surface to the level of the base metal.

1.3.3 Improvement of fatigue strength of fusion welded joits by microstructural refinement:

It is possible to refine microstructure of fusion welds in terms of proper grain structure and morphology by heateatments like annealing, normalizing or hardening and tempering. However refined structures obtained through various conventional treatments have not clearly demonstrated any positive gain in fatigue strength.

1.4 Objective of present investigation:

It has been observed that an unconventional treatment called ' thermal cycling,' which involves heating and cooling repeatedly through a temperature range during which phase transformation can occur in a given material in solidsstate, can lead to fine grained structure. Such a treatement is expected to lead to homogenity in welded structure accompanied by grain refinement.

The main objective of the investigation reported in this thesis therefore concerns with the study of thermal cycling treatement on the structure and fatigue behaviour of fusion welded joints in mild steel.

CHAPTER II

REVIEW OF LITERATURE

Presented in this chapter is a review of literature concerning fatigue strength dependent on grain size and fatigue crack propagation in welded joint.

2.1 Grain size effect on fatigue strength:

It has been verified by several investigators[4] that α-iron and its dilute solid solution follow the following equations:

$$\sigma_o = \sigma_i + K d^{-1/2}$$
$$\sigma_e = \sigma_i' + K' d^{-1/2} \qquad (2.1)$$

where σ_o is the lower yield point, σ_e the flow stress, σ_i and σ_i' the friction stress, K and K' are constants, and d is the grain size.

It has been found by Sinclair and Craig[5] that the fatigue limit also depends on grain size in the same way as σ_o and σ_e .

$$\sigma_c = C_1 + C_2 \, d^{-1/2} \qquad (2.2)$$

where σ_c is the fatigue limit, C_1 and C_2 are constants. This equation has been verified for both substitutional[6] and interstitial solid solution.

Klenil, Halzmann, Lukas and Rys[5] had worked on 0.11% carbon steel, and it was found that when a low stress amplitude is applied the resulting values of frictional stress and strain amplitude are independent of the gain size. but the life of the specimens and the fatigue limit both depend on grain size (see fig.-2.1) It was explained that the blocking effect of grain boundaries on the spreading of persistant slip bands plays an important role in the latter stage of the fatigue process.

It is reported [7] that, the S-N curves for fine-grained specimens exhibit a sharper bend and become more nearly parallel to the N axis at higher stress level than those for coarsed grain specimens, regardless of the testing temperature.

2.2. Variation of fatigue crack growith rate with ferrite grain size:

The variation of fatigue crack growth rate with ferrite grain size in the pearlitic alloys is shown in fig.- 2.2 based on the work of Aita and Weertman [8].

It was found that an increase in mean ferrite path corresponds to an increase in crack rate.

Similar crack growth rate was observed for hot-rolled Fe-0.04% C (15 μm ferrite grain dia, 5 Vol.pct.

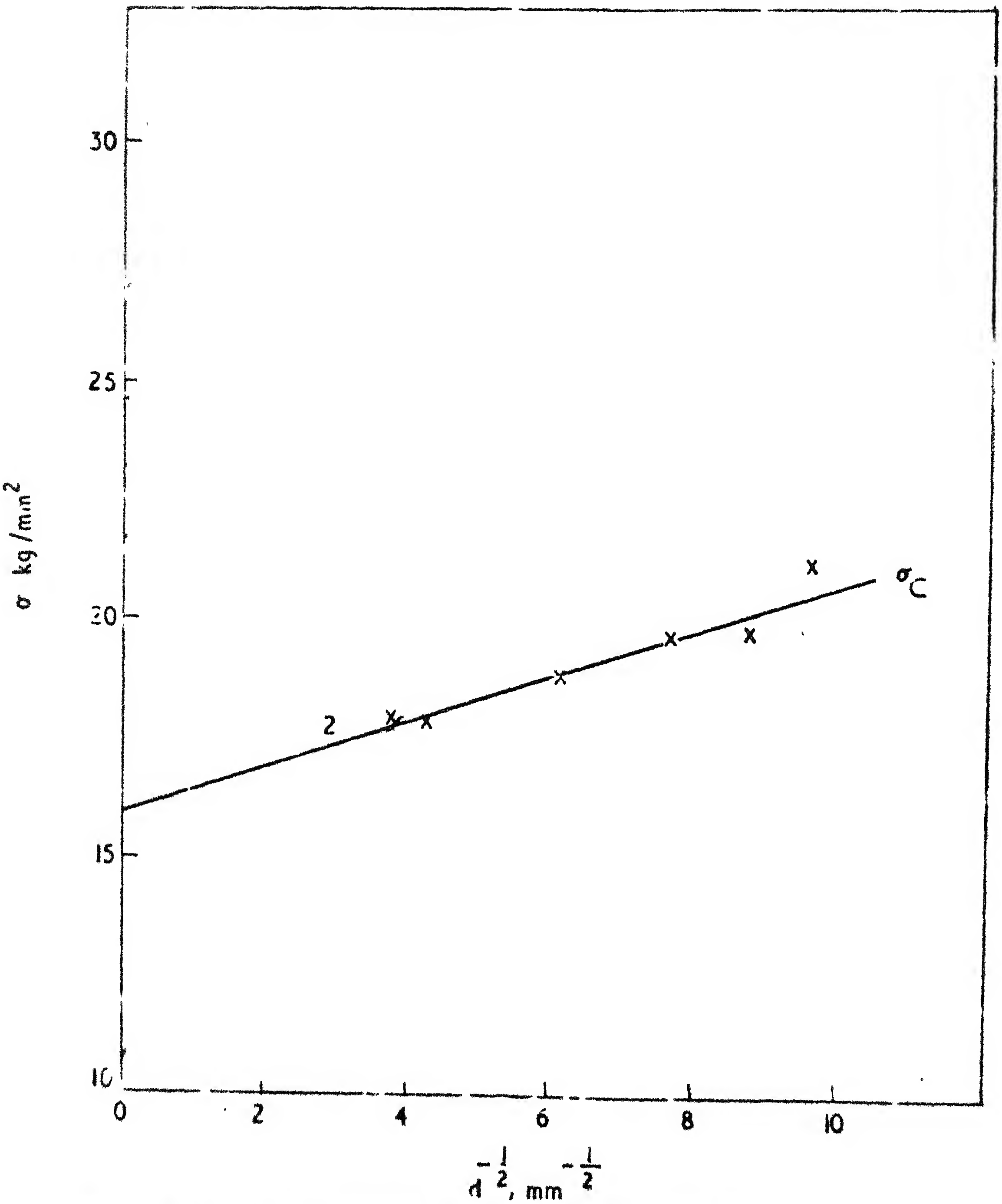
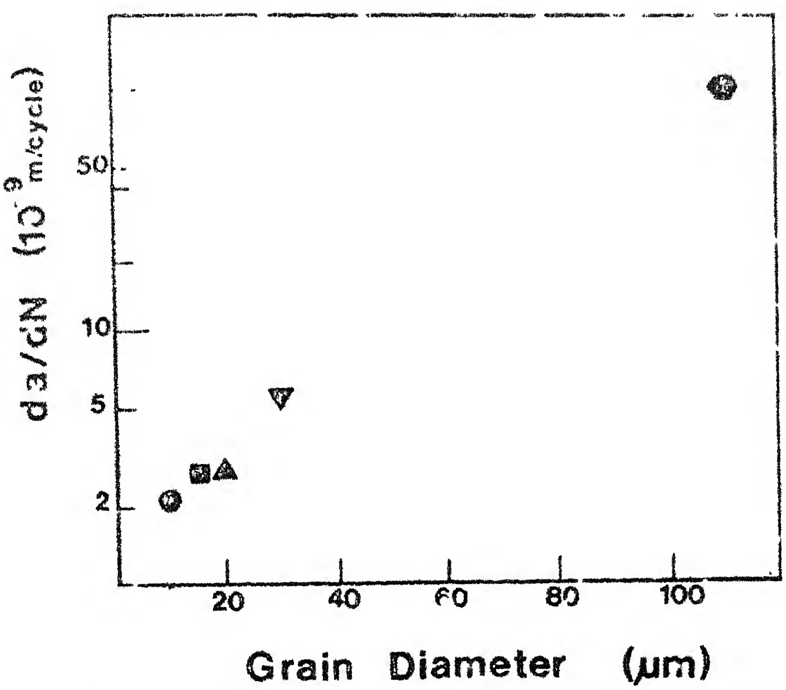


Fig. 3.1 Influence of grain size on fatigue property of low C- steel.



-Variation of fatigue crack growth rate with the fer- grain size in pearlitic alloys ~~which obey Eq. [1] with *m*~~

pearlite) and annealed Fe- 0.45% C (20 μm ferrite grain dia, 55 Vol. pct. pearlite). ~~has similar crack growth rates~~. The path of cracking was found preferentially through the free ferrite. It was observed that as long as there was a continuous ferrite path for the crack to follow, the effect of pearlite amount, morphology, and distribution is secondary. In general pearlite colonies act as mechanical barriers to the growing crack .

2.3 Fatigue crack propagation in weld metal and HAZ-:

It has been observed by several investigators[9] that the rate of growth of ferrite crack in weld metal and heat affected zone (HAZ) are also related to the instantaneous value of stress intensity factor and they follow the relation

$$dl/dN = A\,(\Delta K)^m \qquad (2.3)$$

where ΔK is stress intensity factor corresponding to the range of applied stress $\Delta\sigma$.

A and m (value of m varies from 2 to 3) are material constants.

The equation may be written in the form,

$$\ln\,(dl/dN) = \ln A + m \ln \Delta K \qquad (2.4)$$

which is an equation of st. line.

The rate of crack propagation can be obtained by the slope of the plot between crack length and no. of cycles of applied load (N).

The range of stress intensity factor ΔK can be calculated simply by using relation (for plain strain, mode I crack propagation)

$$\Delta K = y \Delta \sigma \sqrt{\pi l}. \qquad (2.5)$$

ln (dl/dN) vs lnΔK plot is shown in fig.- 2.3.

2.4 Effect of grain size on formation of propagating fatigue crack:

Fig.-2.3 representing dl/dN vs Δ K, shows a critical value of the stress intensity factor ΔK_e, below which a fatigue crack will not propagate.

Forrest and Tate[10] report that stage I microcracks extend over the length of one grain only. They found that an edge fatigue crack of length l in a plate subjected to a cyclic stress $\pm\Delta\sigma$ would not grow if the parameter $\Delta\sigma^3 l$ was less than a material constant C (independent of grain size). This indicates that the fatigue limit increases as the grain size decreases.

2.5 Fatigue crack path:

For the rate of crack propagation in the weldment and HAZ work has been done by Dawas and Richards [11].

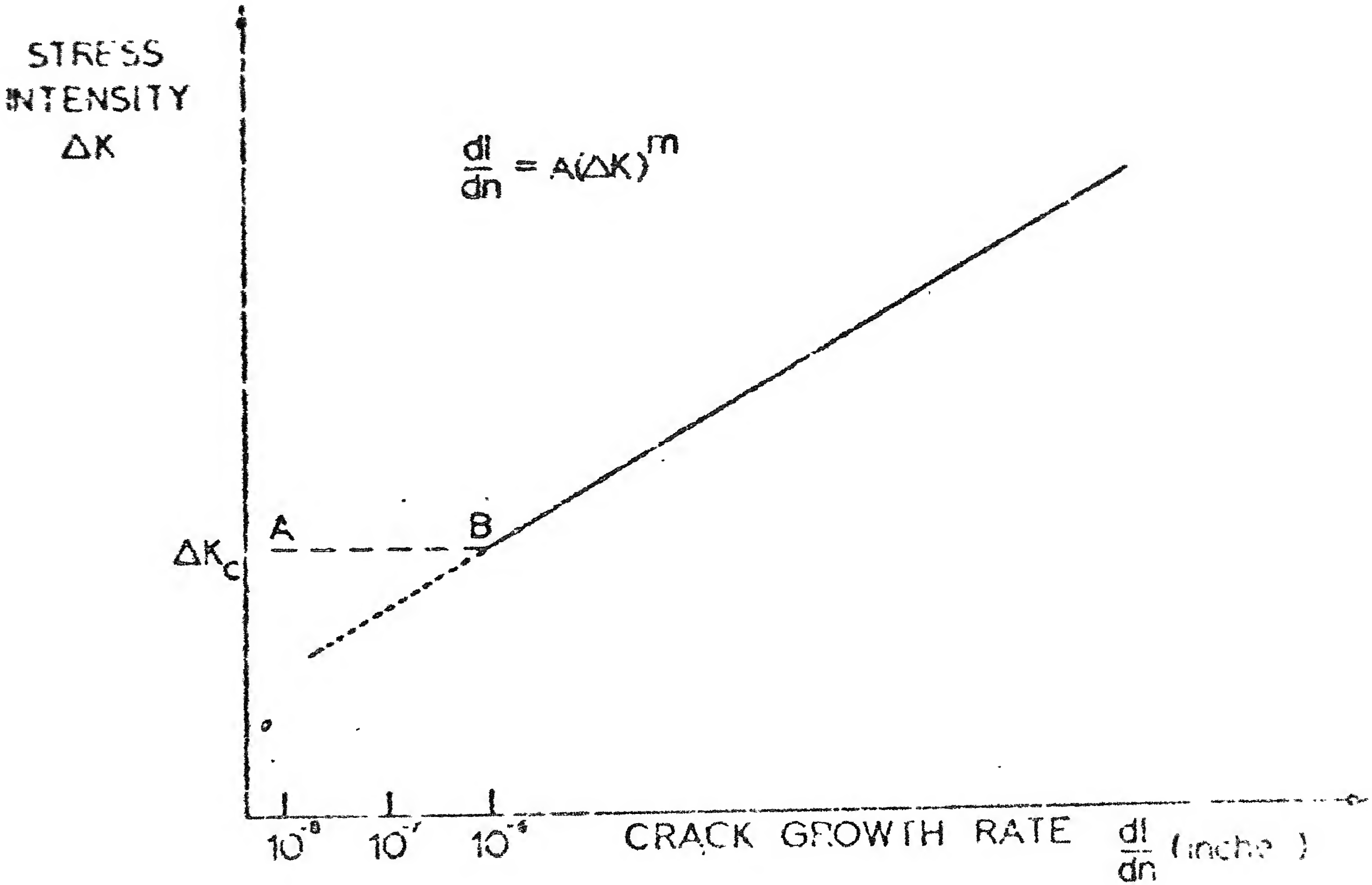


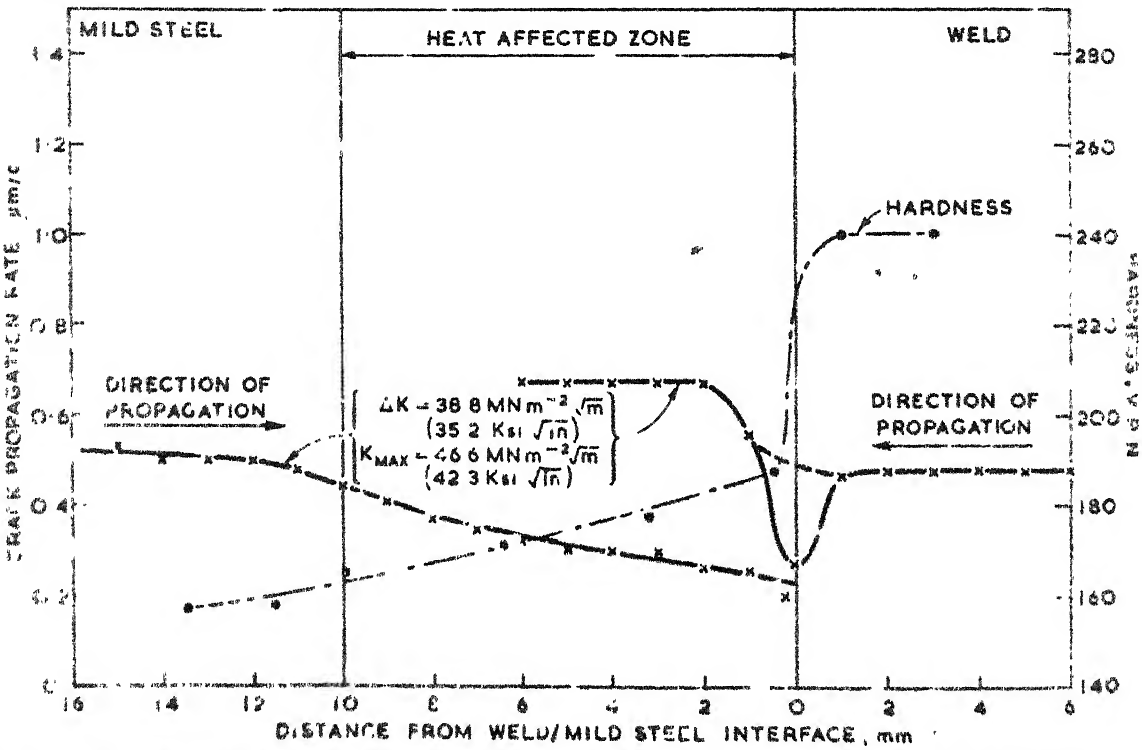
Figure 2-3 Fatigue crack growth rate vs the amplitude of the stress-intensity factor.

Two tests were performed at the same conditions of ΔK and Kmax. with a HAZ lying 75° to the tensile axis. In one test the crack was propagated from the mild steel towards the weld and again the crack started to slow down before the crack tip reached HAZ (see fig.- 2.4). Crack did not penetrate the weld metal and propagated parallel to the interface with slowest rate.

In the other test the crack was propagated from the weld to the parent metal. Apart from one point at the interface the rate of propagation increased on passing from the weld to HAZ. The low value of propagation rate at the interface was attributed to a sharp change in crack direction as the crack moved parallel to the tensile axis for a short length. It was found that the crack propagation rate in the HAZ, for identical testing conditions depends on the direction of propagation, the rate being faster when crack propagated towards the mild steel than towards weld.

2.6 Effect of heat-treatment on fatigue property of welds:

Tests on fillet welded low alloy steel specimens(12) showed that, heat-treatement in vacco at 960°C for 1 hr. eliminated the HAZ structure and the final structure was the same as that of the parent plate. A reduction in the hardness of the zone was found. The fatigue



ig.24—Variation in crack propagation rate and hardness long the fatigue crack path through a mild steel H.A.Z. at .. deg to the tensile axis.

strength of these heat treated specimens was approximately 8 tons/ in^2 compared to 12 $tons/in^2$ for the as welded specimens. Hence, when the suspected HAZ structure was removed by annealing the fatigue strength decreased rather than increase.

Gurney[13] has reported that normalising produces a small increase in strength both in mild steel and low alloy steel. Reason of improvement is supposed to be the relief of residual stress.

Effect of thermocyclic treatment on the tensile properties of the welded joint is done by Vargosov, Mansurov and Titov [14]. Specimens were subjected to thermocyclic treatment, consisting of vacuum heating of the specimens to $950^{\circ}C$ with the rate of 15-$20^{\circ}C/$ Sec. followed by cooling with the rate $10^{\circ}C/$ Sec. An increase in UTS (from 45 to 56 Kg mm^{-2}) and yield strength (from 31 to 41 Kg mm^{-2}) was found.

CHAPTER III

EXPERIMENTAL PROCEDURE

Experimental procedure of the present work is presented in this chapter.

3.1 Materials:

Mild steel plate of 3/8 in. thickness was used as base metal in the present investigation and welding was carried out by mild steel electrode (IS:E 614-411). Chemical composition and tensile test results of the steel plate are given in tables 3.1 and 3.2 respectively . Details of the electrode is given in table 3.3.

Table 3.1

Chemical composition of the steel plate

Element	C	Mn	Si	S	P
Wt %	0.10	0.93	0.14	0.016	0.02

Table 3.2

Tensile test results of steel plate

Yield Stress Kg/mm^2	UTS Kg/mm^2	% Elongation
29.6	40	36

Table 3.3

Details of electrode IS: E 614 411

Carbon content-0.11%

Method of manufacture- solid extrusion,

Flux - Calcium carbonate and fluoride.

Tensile test results

Yield stress Kg/mm^2	UTS Kg/mm^2	% Elongation
30	41	20

3.2 Welding Procedure:

Mild steel plate was cut into $20 \times 17\ cm^2$ pieces and double 60 degree shape was given to long edges of the plate pieces, shape and di-mensions of the plate is shown in fig. 3.1. At a time two edges prepared plate pieces were taken and welded by manual arc welding process. Then $20 \times 34\ cm^2$ joined plates were cut into $2 \times 34\ cm^2$ pieces.

3.3 Heat - treatment:

In the present experiment welded steel pieces were thermo-cyclic treated. The upper and lower critical temperature for the alloy were 890°C and 723°C respectively.

Pieces were heat-treated by oxyacetylene flame and a very few in furnace. Before the heat-treatment of the

samples by oxyacetylene gas tourch, were cleaned to remove oxide scale from the surface and the hot junction of the thermocouple was welded on one of its faces at the centre of weld metal. A region near the weld metal (approximately 2 in. on either sides of weld metal) was heated by flame. During heating the flame length and its distance from piece was kept constant to attain a constant heating rate. As soon as thermocouple had indicated 910°C (20°C above Ac_3), the flame was removed and piece was allowed allowed to cool in air. When temperature decreased to 650°C it was again heated by flame up to 910°C and the process was repeated for five times. Heat treatment cycle is shown in Fig. 3.2.

The pieces for heat treatment in furnace, were kept in the furnace maintained at temperature 915°C for 20 min. and after that they were withdrawn from it and allowed to cool in air up to 650°C . Pieces were again placed in the furnace for 5 min. and process was repeated for five times.

3.3 Specimen for Fatigue Testing:

Specimens for testing fatigue strength were prepared from the 2 x 34 cm^2 pieces. Dimension of the sample are shown in the Fig. 3.3(a). The longitudinal axis of all specimens was kept parallel to the rolling direction of the parent plate.

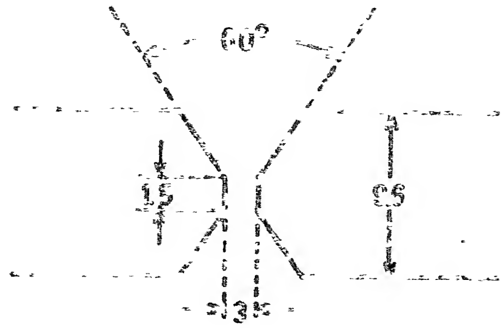


Fig. 3.1. Details of the edges for welding.

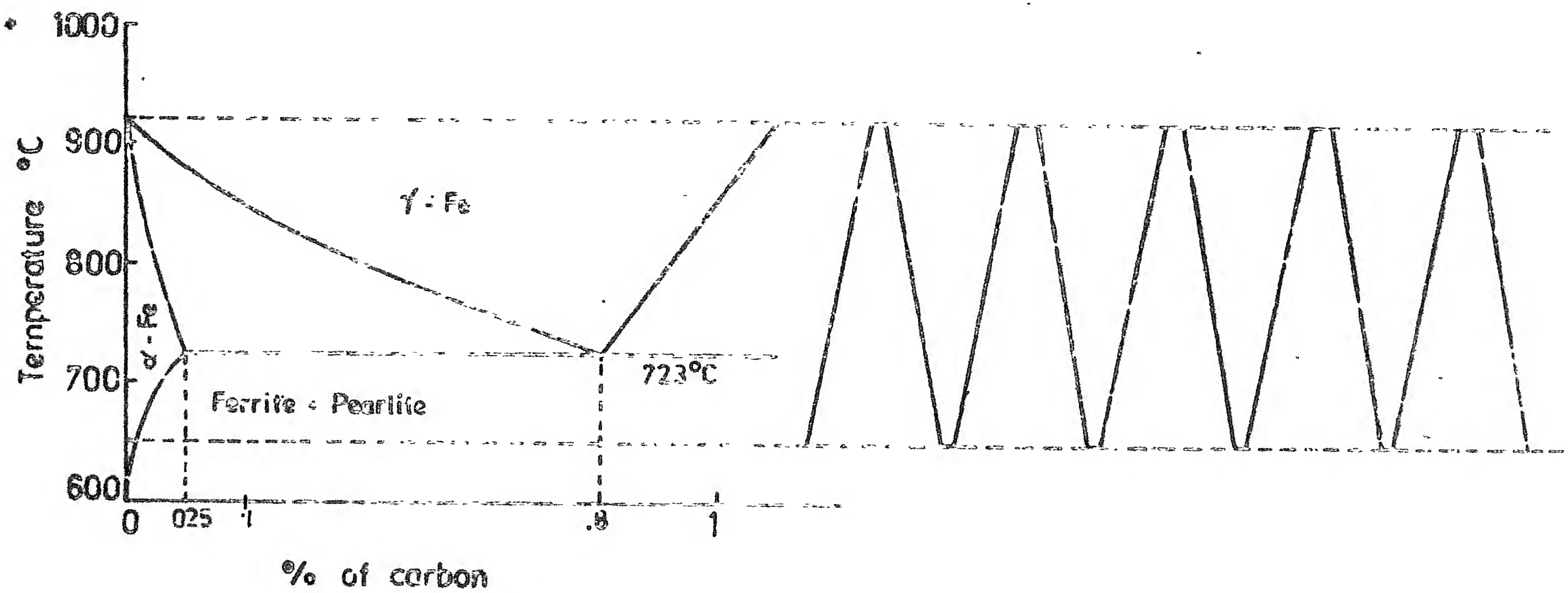


Fig. 3.2. Fe - C equilibrium diagram and heat treatment cycle.

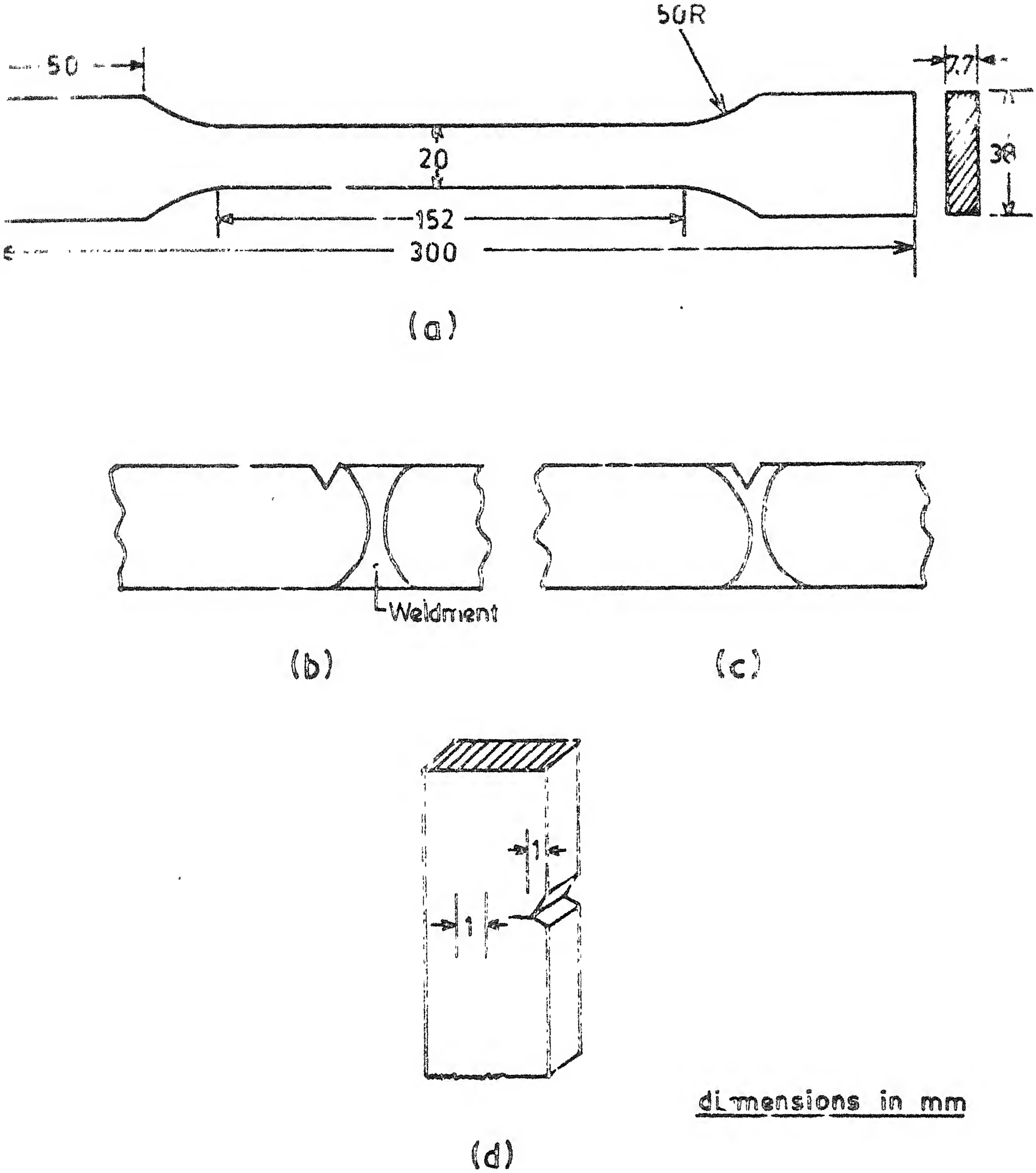


Fig. 3.3. (a) Fatigue test specimen.
(b) Position of the notch in HAZ.
(c) Weldment
(d) Notch and lines for measurment of crack rate.

For making notch at the desired location in the weld zone, some specimens were macro etched in the hot HCl acid. V-notch (45° and 1 mm deep) were made at HAZ close to weld-ment or at weldment. Specimens were repolised before test.

3.4 Fatigue testing:

Fatigue test was done on MTS 810 system. For all tests, pulsating tensile stresses with minimum stresses of zero, were used and all the time load cycles had Haver sine shape . All specimens were tested within frequency range of 15 to 25 Hz.

First set of experiments was done on specimens without notch. The stress levels were decided on the basis of the UTS of the parent material (because fatigue strength of steel is approximately 0.5 of the UTS) and tests were carried out on untreated and heat-treated samples for determination of fatigue life of samples corresponding to the applied stress.

Second set of tests were done on untreated and gas tourch thermocyclic treated (GTT) specimens having notch at HAZ, close to weld metal.

For measurement of crack propagation rate lines were drawn at equal interval (1 mm) on the width face of the specimens (see Fig.-3.3 (d)). When crack started

propagating the number of cycles were noted against position of the crack tip as well as fatigue life corresponding to that stress were noted down.

Third set of experiments was done again on untreated, GTT and furnace thermocyclic treated (FTT) specimens but notched at weldment. Crack propagation rate and fatigue life corresponding to various stress level were measured.

CHAPTER IV

RESULTS

Thermocyclic treatement results into changes in microstructure, hardness and fatigue behaviour of the welded joint. Changes in all these observed properties are presented in this chapter.

4.1 Microstructure:

Microstructures of different zonesof treated and untreated samples are given here.

4.1.1 Unheat-treated:

Microstructures of untreated weldment are shown in fig.- 4.1 and 4.2. It is clear from above two figures that microstructure in the weldment is not same. Actually two distinct structures are a characteristic feature of multi-pass welding. Annealing of first deposited metal took place due to the subsequent process of metal filling.

Microstructure of HAZ close to the weldment is shown in fig.-4.3. Widmanstatten structure was observed in that region.

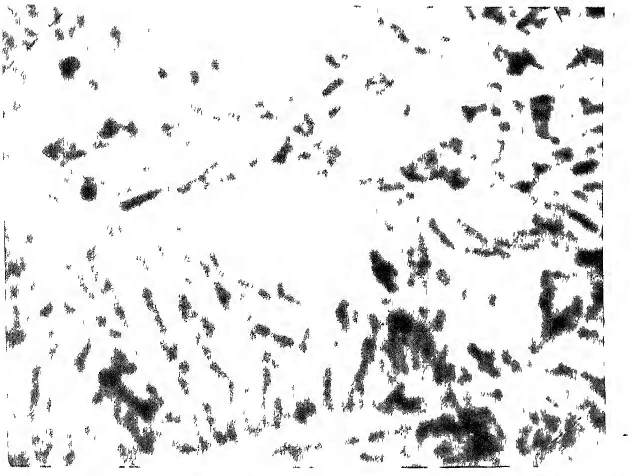


Fig. 4.1

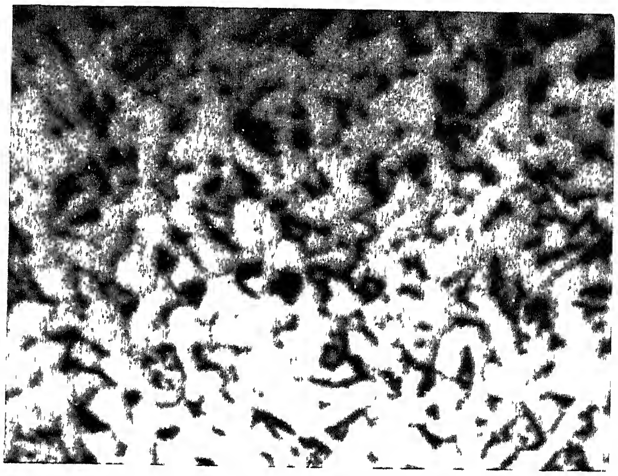


Fig. 4.2

Fig. 4.3

Optical micrographs of different zones of unheat-treated sample.
4.1 Weldment, 450x, 4.2 Heat affected layer of weldment, 450 x
4.3 Heat affected zone of parent metal close to weldment, 450 x.

4.1.2. Gas tourch thermocyclic treated (GTT) sample:

GTT changes the structure of the weldment into equiaxed grains, shown in fig- 4.4 and 4.5. Grain size, not found uniform throughout the cross-section. A slightly finer grains were observed (Av. grain size 9.8μ, fig.- 4.5) on the surface than interior metal (Av. grain size 13.91μ , fig.- 4.4).

This treatment also changes the structure of HAZ adjacent to the weldment into equiaxed grains, as shown in fig.- 4.6. Though it was found coarser than deposited metal and average grain size was 18.09μ.

4.1.3 Furnace thermocyclic treated (FTT) sample:

Microstructured changes in the weld metal due to FTT is shown in fig.- 4.7. Almost uniform sized equiaxed grain were found in the region, and average grain size was 13.82μ.

Microstructure of HAZ under consideration is shown in fig.- 4.8. It is clear from the micrograph that this treatement also changes it into equiaxed grains and average grain size was 16.61μ.

4.2 Hardness measurement results:

The hardness measurement results of the welded joint are shown in fig-.4.9. Untreated sample was found to be

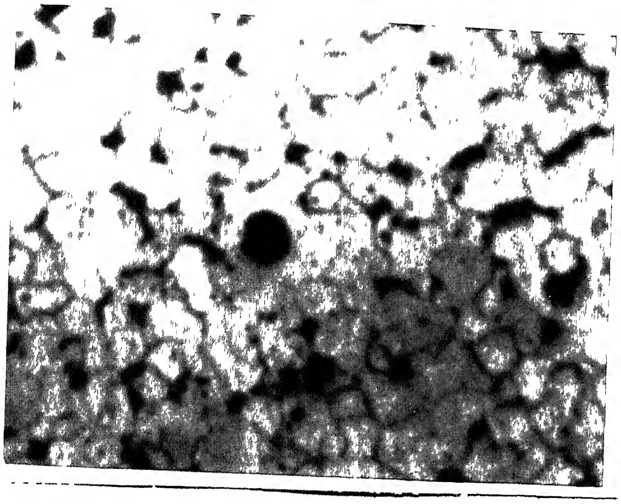


Fig. 4.4

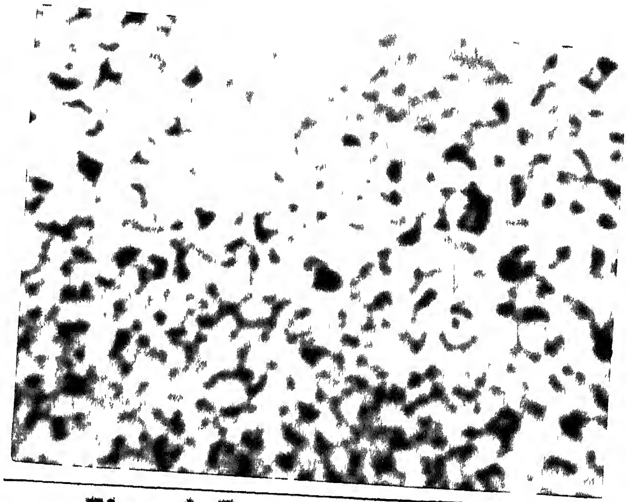
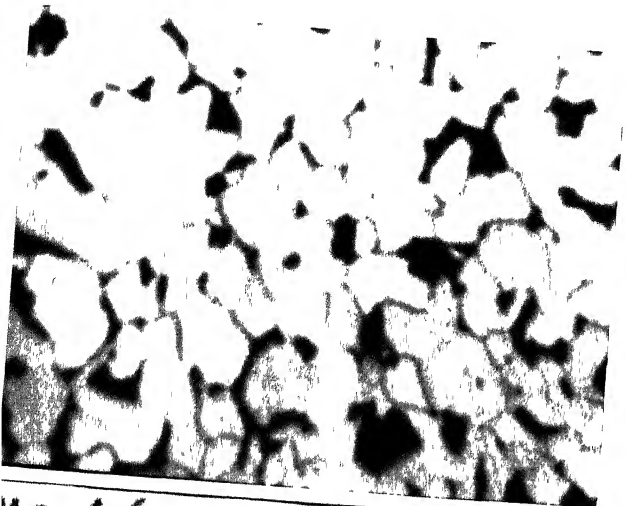


Fig. 4.5



'ig. 4.6

ptical micrographs of different zones of JFT sample

.4& 4.5 Two different regional of weldment 450x

HAZ of parent metal. 450x

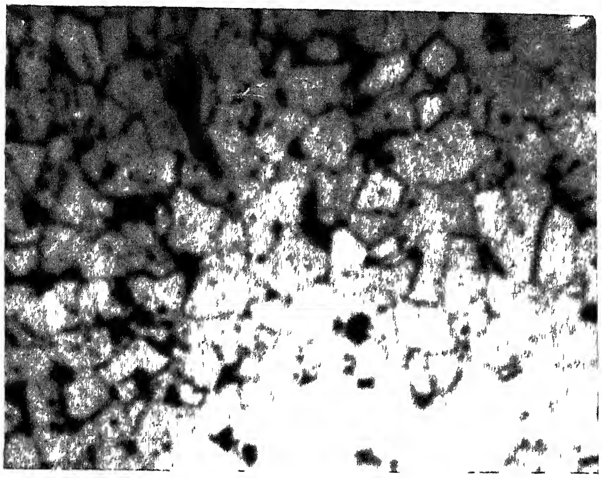


Fig. 4.7

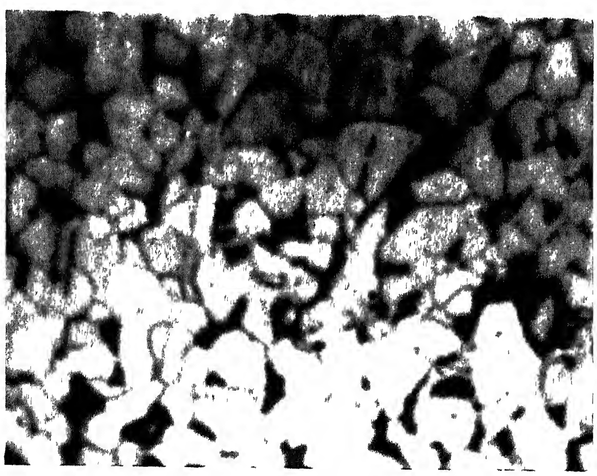


Fig. 4.8

Optical micrographs of different zone of FTT sample

4.7 Weldment 450 x

4.8 HAZ of parent metal 450 x.

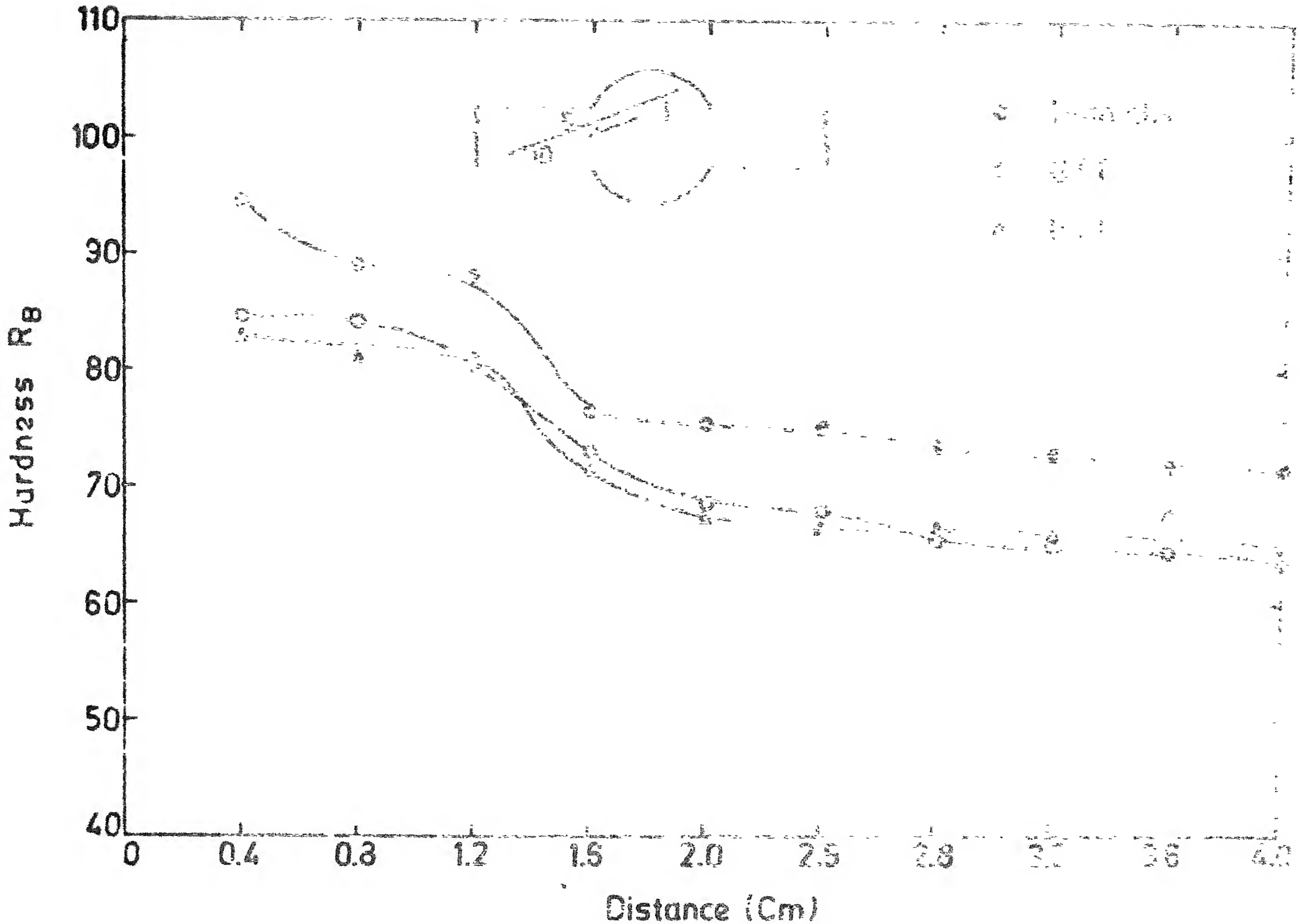


Fig. 4.9. Hardness Vs Distance plots for treated (GTT & FTT) and untreated samples

harder than both GTT and FTT samples. Maximum hardness was found in each case near the surface in the weldment and has reduced to a lower value as moved away from it. The maximum hardness observed on the untreated, GTT and FTT samples were R_B 94.7, R_B 84.5 and R_B 83 respectively. From hardness profile, it is clear that hardness at each point on the heat-treated samples are less than that of the untreated one. Hardness profile of FTT samples shows that, value is almost constant throughout HAZ, where as it was not observed in case of untreated and GTT samples.

4.3 <u>Fatigue test of unnotched specimens</u>:

In the first set of experiments untreated and GTT unnotched specimens were tested. Most of the specimens after failure showed defect (slag inclusion) in the weldment region.

The data when plotted in terms of stress vs no of cycles to failure was found to be scattered. Then actual load carrying area was determined for each sample by subtracting the defective area from the weldment cross-section. After that; cycles to failure were plotted against the effective stress level, shown in fig.- 4.10 and data is given in table 4.1. It indicates that for a particular stress level fatigue life of untreated specimens is more than that of the GTT one.

Table 4.1

Fatigue test results for , GTT and untreated specimens, without notch.

S.No.	Untreated/GTT specimens	Effective stress Kg/mm^2	No. of cycles to failure
1	GTT	36	2.92×10^4
2	-do-	32.7	7.03×10^4
3	-do-	29.7	2.45×10^5
4	-do-	28	2.1×10^5
5.	-do-	26.4	1.02×10^6
6.	Untreated	36.1	5.73×10^4
7.	-do-	34.8	2.09×10^5
8.	-do-	32	2.05×10^5
9.	-do-	27.4	1.28×10^5
10.	-do-	27.6	1.32×10^6

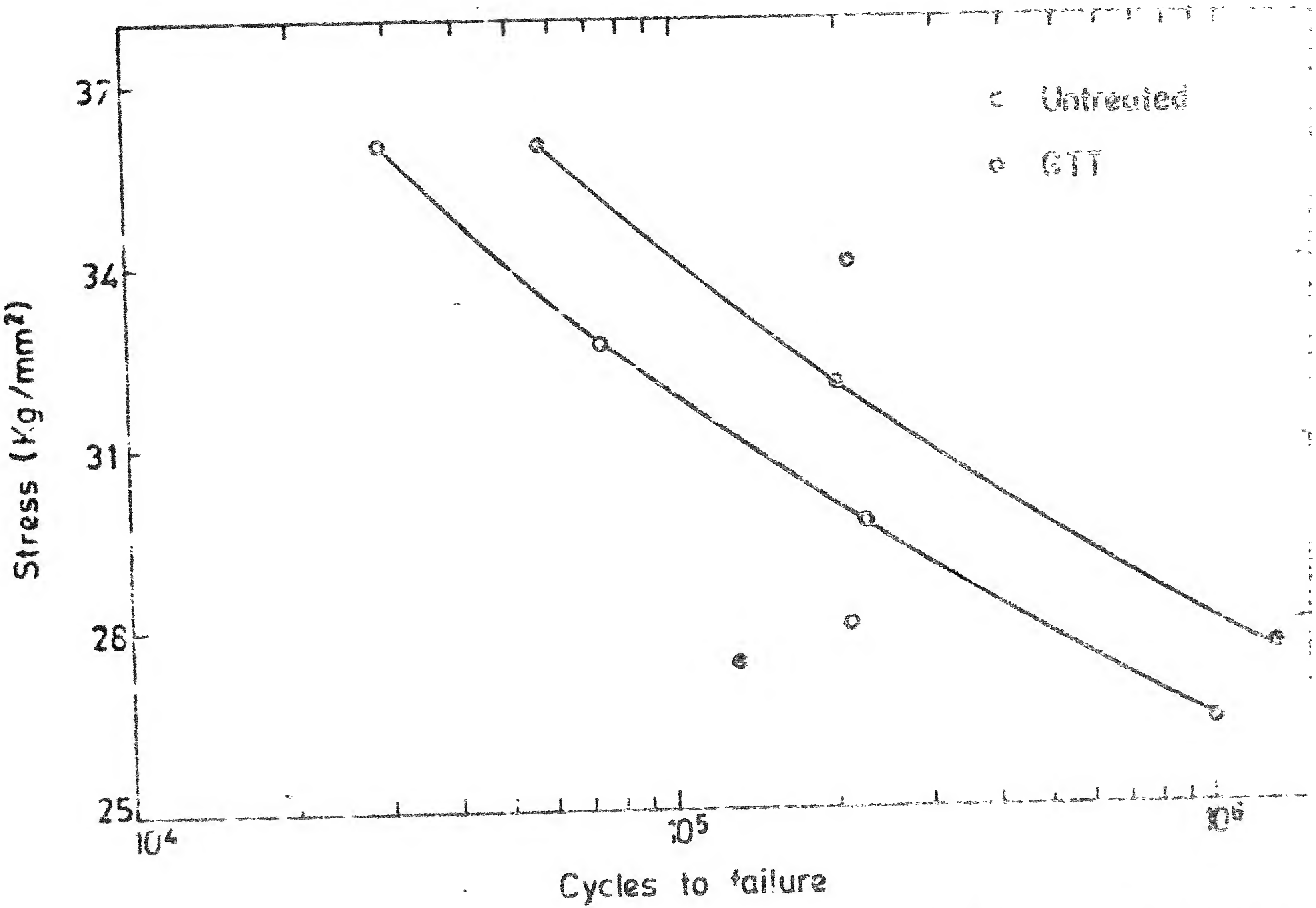


Fig. 4.10. S-N curves for untreated and treated (GTT) unnotched specimens.

The difference in life is found less at lower stress values.

4.4 <u>Fatigue test of specimens having notch at HAZ</u>:

In the second set, specimens having notch at HAZ (close to the weldment) were tested. Test data and S-N curvesfor the untreated and GTT specimens are given in the table 4.2 and fig. 4.11 respectively. Thermocyclic treated specimens have shown a considerably lower life than the untreated specimens at higher stress level, for example, fatigue life of untreated sample at 24 Kg/mm^2 stress level was 6.9×10^4 cycles, where-as for GTT samples it was only 4×10^4 cycles. The difference in the fatigue life goes on decreasing as moved towards the lower stress value and both (untreated and GTT) show almost same life at a stress level 20 Kg/mm^2.

Relation (2.4) was used for measurement of crack propagation. Fig.-4.12 illustrates crack propagation rate in HAZ adjacent to the weldment. For a particular stress level,it was noted that first one mm propagation of crack in the untreated specimens consumed higher no. of cycles than that by GTT specimens, though further propagation of crack was faster in untreated. But higher stress level has recorded almost equal rate of crack propagation in either case. It was also found that for

Table 4.2

Fatigue test results for untreated and GTT specimens having notch at HAZ .

S.No.	Stress level Kg/mm2	Cycles to failure for Untreated specimens	GTT Specimens
1	26	4.6×10^4	3×10^4
2	24	6.9×10^4	4×10^4
3.	22	1.1×10^5	2.6×10^5
4.	21	1.45×10^5	1.2×10^5
5.	20	4.7×10^5	3.8×10^5
6.	20	5.7×10^5	4.65×10^5

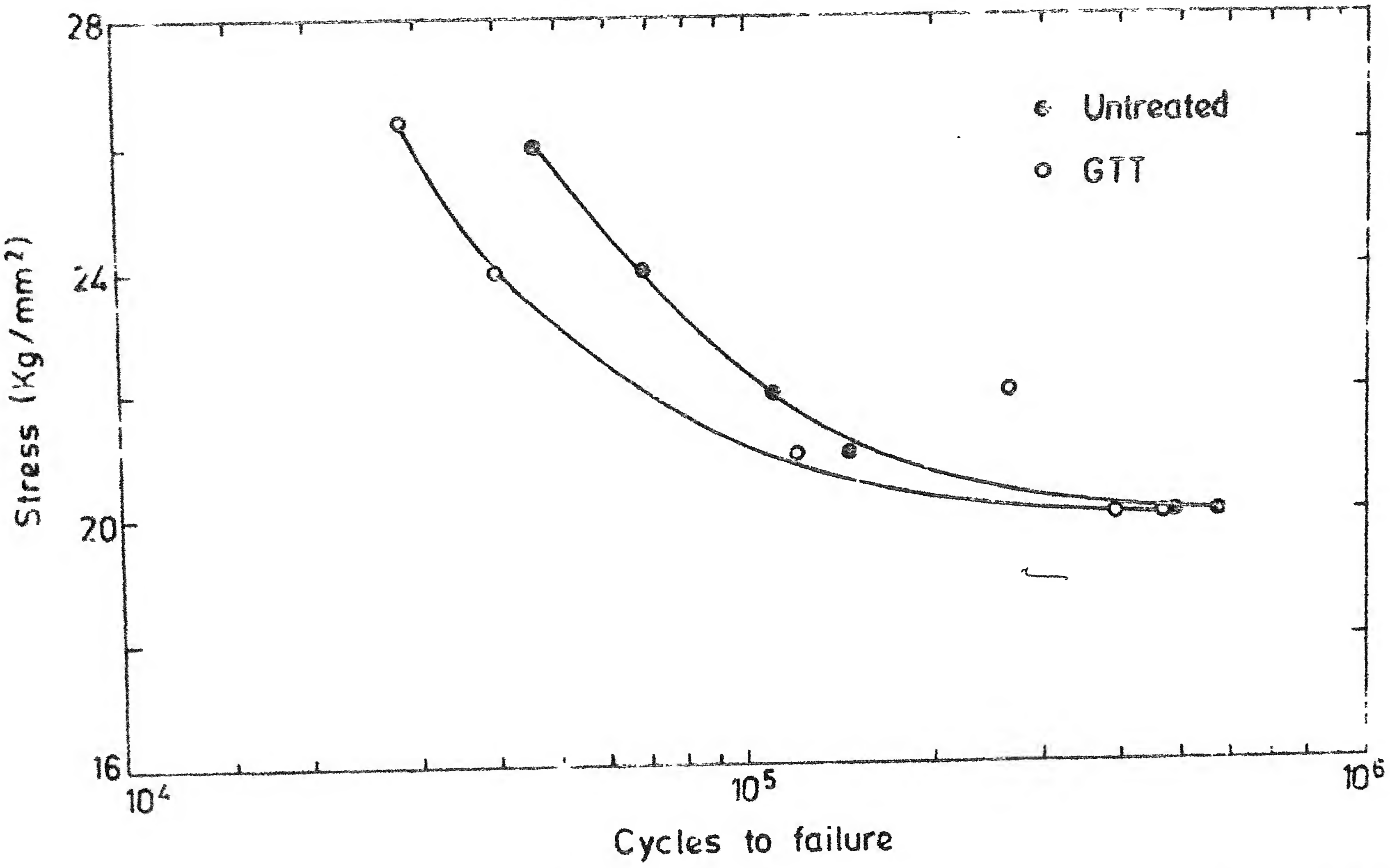


Fig 4.11. S-N curves for treated (GTT) and untreated samples with a notch in HAZ.

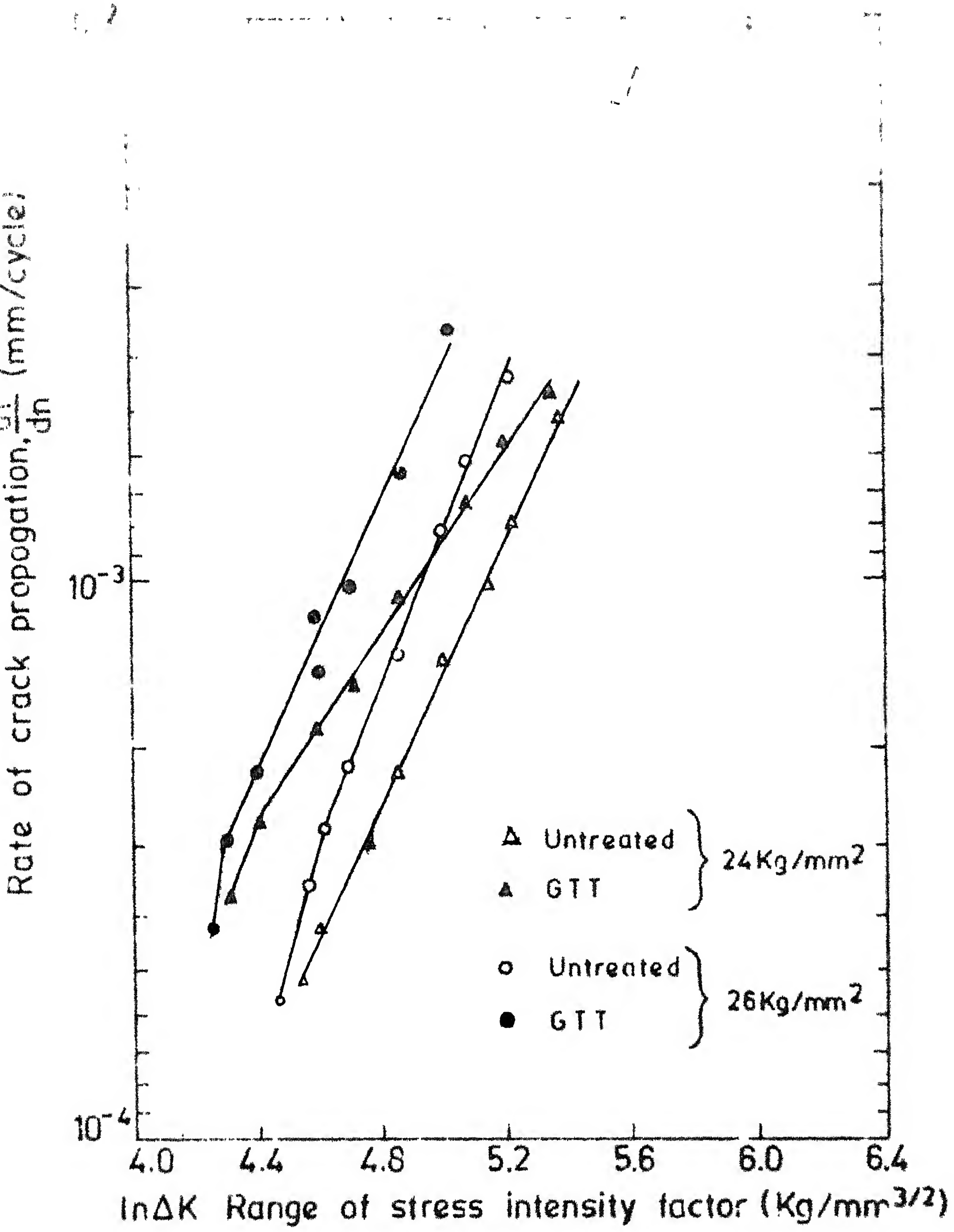


Fig. 4.12. Crack propogation results for specimens having notch at HAZ.

both untreated and GTT specimens, rate of crack-propagation has increased with increase of the applied stress.

4.5 Fatigue test of specimens having notch at weld metal:

Third set of experiment were done on the specimens having notch at weld metal. Untreated, GTT and FTT all three types of specimens were tested in the present set.

S-N curves are shown in fig.- 4.13. ~~respectively~~. Again it was found that thermocyclic treated specimens have a lower fatigue life than as welded specimens at higher stress level. At lower stress level the difference between the fatigue life has reduced considerably. GTT and FTT specimens have shown almost similar fatigue performance.

Observed crack propagation rates are shown in fig.- 4.14, and it was found almost equal for all, types of specimens. Initially crack has propagated in a quite slower fashion and after its deep penetration a rate comparable to its crack propagation rate in the HAZ was observed. First mm crack propagation in the untreated sample was

Table 4.3

Fatigue test results for untreated GTT and FTT specimens having notch at weldment.

S.No.	Stress level Kg/mm^2	Cycles to failure for Untreated specimens	GTT Specimens	FTT Specimens
1	27	6.2×10^4	2.2×10^4	-
2	28	4.2×10^4	-	-
3	26	-	2.7×10^4	3.5×10^4
4	25	1.7×10^5	3.7×10^4	
5	24	4.6×10^5	6.35×10^5	3.8×10^4
6	23	-	2.1×10^5	3.6×10^5
7	23.5	-	-	1.75×10^5

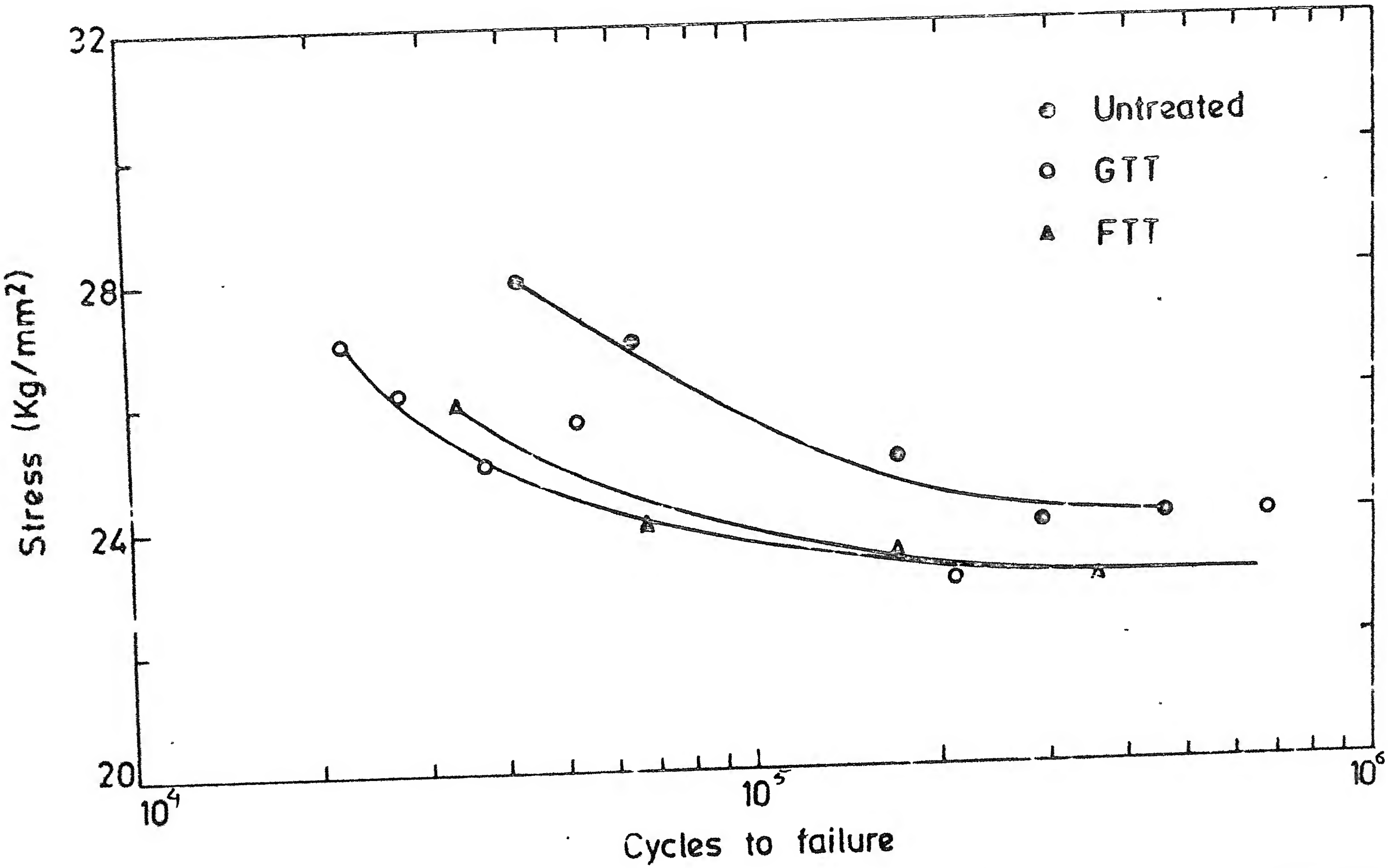
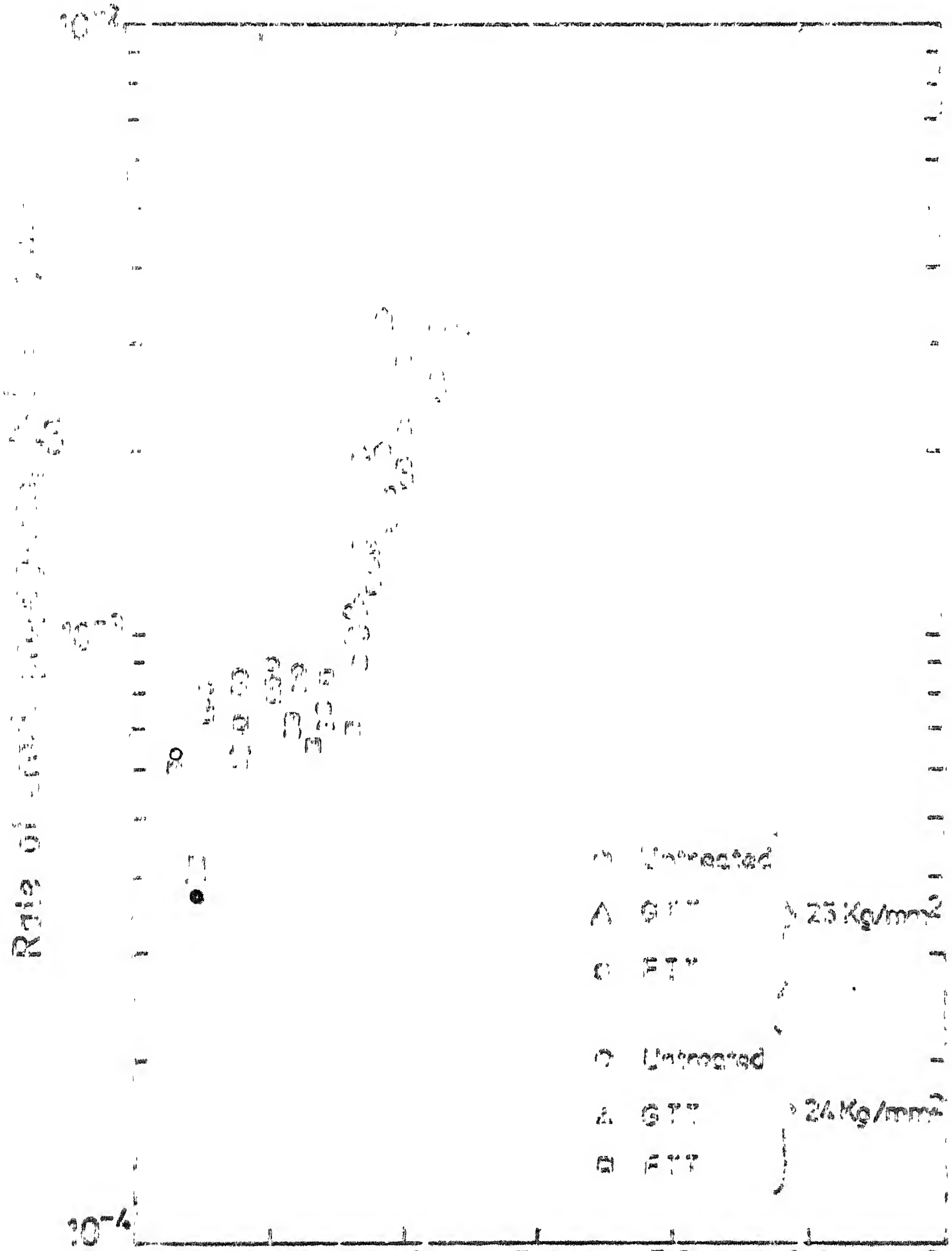


Fig. 4.13. S-N curves for treated (GTT & FTT) and untreated samples with a notch in weld metal area.



ln ΔK Range of stress intensity factor (Kg/mm $^{3/2}$)

Fig. 4.14. Crack propogation results for specimens having notch at weldment.

found slower than GTT specimens.

4.6 Fractography:

The scanning electron fract-ograph for untreated and GTT specimens having notch at HAZ and tested at 20 Kg/ mm^2 are shown in fig.- 4.15 and 4.16. Fractographs were taken at points close to the notch. Characteristic striation marks, were observed and it was found that the space between two striations was less for untreated as compared to the GTT sample.

That is initial crack propagation rate in untreated sample is slower than gas heat treated.

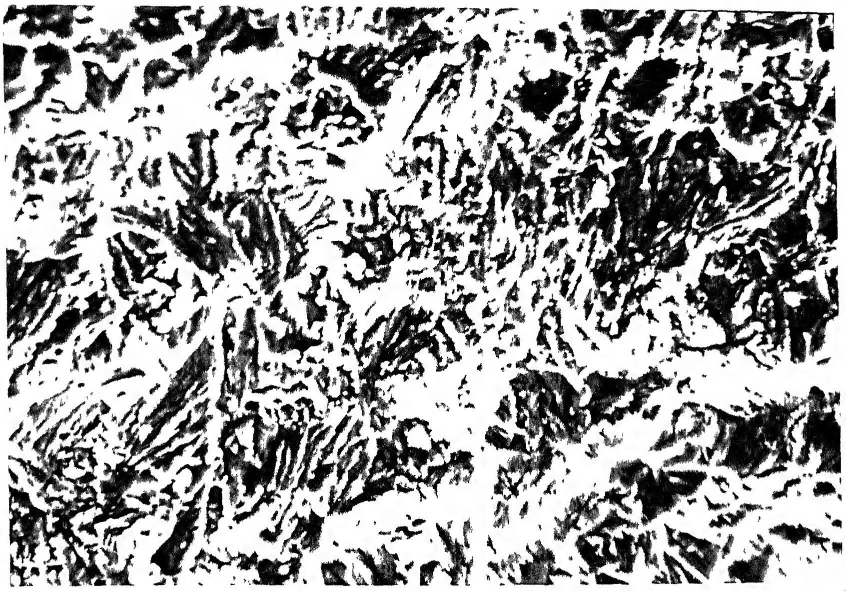


Fig. 4.15

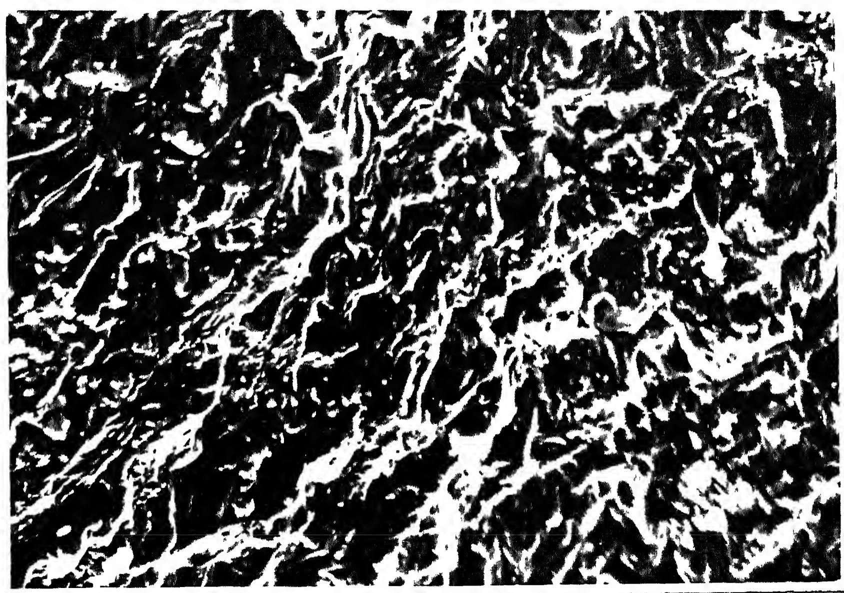


Fig.4.16

Scanning electron microscopic views of fatigue fracture surfaces, of the specimens notched at HAZ and tested at stress level 20 Kg/mm^2

4.15 Unheat treated 600 x

4.16 GTT 600 x

CHAPTER V

DISCUSSION

The results of the present investigation on the effect of thermal cycling treatment on fatigue behaviour of fusion welds is discussed in this chapter.

5.1 Effect of the treatment on Microstructure:

The results indicate considerable changes in the morphology of phases (ferrite and pearlite) due to the heat-treatment. The original cast structure in the fusion zone of the weld has been broken down and there is a grain refinement. During thermal cycling, the repeated dissolution of ferrite and pearlite to austenite and decomposition of austenite back to ferrite and pearlite leads to enhanced nucleation rate which leads to finer grain structure. Further, repeated phase transformation leads to enhanced diffusional flow[15] which helps in rapid removal of segregation of carbon obtained in the cast structure and develope an equilibrium morphology.

Though the grains become equiaxed, the grain size differences between weldment, heat affected zone and parent metal persist in the gas treated samples since heating is confined to the weld area only. Where as in the furnace treated samples the grain size is more

uniform. In the latter case the entire sample is heated and cooled uniformly.

5.2 Effect of the tratment on fatigue behaviour:

Though the grain size is refined and the structure becomes more uniform the expected improvement in fatigue behaviour is not observed. Instead, there is a decreament in the fatigue strength in the low cycle fatigue region.

The possible explainationsfor such an adverse effect could be (i) Precipitation of dissolved.oxygen in the weld zone as iron oxide (Fe_2O_3) and growth of such precipitates during thermal cycling treatment [16]. (ii) Independance of fatigue strength on grain size[17].

It has been demonstrated by Irvine and Pickering[16] that during the metal arc welding process more oxygen goes into the weld metal (0.05-0.2%) than solid iron can dissolve. Owing to the extremely fast cooling rate of the weld metal the oxygen remains in the supersaturated solid solution. In the temperature 20° - 200°C, or below 560°C, oxygen can precipitate in the form of the spinel Fe_2O_3. The diameter of the precipitate particle is about 100-400 Å. The lower precipitation temperature, the smaller is the size of the particles [18].

This precipitation and growth of oxide particles is also a time and temperature dependent phenomena it has been observed that size of the precipitate exponentially increases on the temperature of annealing. During the thermocyclic treatment enormous coarsening of the precipitates might have taken place and it might be the cause of lower fatigue strength of treated sample at high stress level.

Further it has been shown by Pelloux[17] that metals with wavy slip character during plastic deformation show negligible grain size effect on the fatigue behaviour. Iron and its alloys exhibit wavy slip characteristics and it is expected that their fatigue strength would be independent of grain size.

5.3. Crack propagation in weldment and Heat affected zone:

The results of the fatigue test on notched specimen indicate that : (i) the initial rate of crack propagation (distance 1 mm) in the untreated sample is considerably slower than that in the treated samples (ii) the rate of crack propagation is faster beyond 1 mm in the untreated samples as compared to that in the treated ones.

These two contradictory results may be rationalized on the basis that the threshold stress for the crack propagation in the untreated samples is higher than that in the treated samples. The higher threshold stress of the untreated welds may be because of its lower oxide precipitate contents and higher dislocation density[19].

The difference in crack propagation in HAZ and weldment is primarily due to expected ductility differences in the two regions. HAZ is normally an embrittled zone[20] where as the weldment is relatively ductile.

CHAPTER VI

CONCLUSIONS

Following conclusions are drawn from the present work:

1. Thermal cycling treatment refines the grains in both weld and heat affected zones of a fusion welded joint.
2. The fatigue behaviour of fusion welded parts is adversely affected by thermal cycling treatment. The difference increases with increasing stress amplitude.
3. Threshold stress for crack propagation in untreated weld is higher than that for the treated one.
4. Crack propagation is faster in HAZ as compared that in weld metal. So, a defect in weldmetal will be less dangerous than the one in HAZ.

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